A PHOTOELECTRIC SKYLIGHT POLARIMETER

By

T. A. HARIHARAN

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Feasibility Studies on Co-ordinated Radiation Experiments

from Earth Oriented Meteorological Satellites

Professor Z. Sekera

Project Director

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ABSTRACT

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A photoelectric skylight polarimeter to measure directly the Stokes parameters for plane polarized light is described. The basic principle of the instrument consists in the simultaneous measurement of the intensity of light (in the chosen spectral region) transmitted by polarizers oriented in four specific directions. The main features and performance characteristics of the instrument and associated equipment are discussed in detail.

Author

1. Introduction

This report is concerned with a detailed description of a photoelectric polarimeter developed for the purpose of measuring the polarization characteristics of skylight in the visible region of the electromagnetic spectrum. The instrument is developed as part of feasibility studies on coordinated radiation experiments from earth-oriented meteorological satellites to improve the information content of the channels in the visible region by measuring the polarization of the radiation field in addition to the intensity.

The significance of the measurement of the intensity and polarization characteristics of skylight has been discussed in detail in the review articles by Sekera (1957) and Bullrich (1964). The techniques of observations of skylight polarization have been considerably improved since the first attempt by Sekera (1935) on continuous photoelectric measurement. In addition to ground-based measurements, high altitude observations using aircrafts or balloons have been attempted by several investigators. Instruments suitable for ground-based observations are not always quite satisfactory for high altitude studies, particularly those involving high-speed jet aircraft. The main limitation arises from the rotating or vibrating elements in the instruments. The possibility now exists of measuring the polarization of the visible radiation emerging from the top of the earth's atmosphere from an instrument in a spacecraft. The problems involved are much more severe in satellite applications. The development of the instrument described in this report is primarily guided by spacecraft application. It is the result of studies on the design of a simple, but reliable instrument containing as far as possible no rotating or vibrating components.

Sekera and collaborators (1963) have described a photoelectric skylight polarimeter which employs a rotating half-wave plate and a fixed polarizer. A variable neutral density filter is made to function as a light limiter to maintain the d.c. component of the photocurrent constant. If measurements are confined to the sun vertical, the intensity and polarization can be obtained in terms of the angular position of the neutral density wedge and the amplitude of the fourth harmonic of the rotation of the retardation plate. Gehrels and Teska (1963) in their measurement of the wave length dependence of polarization have used a Wollaston prism followed by two photomultiplier tubes. For different orientations of the Wollaston prism, a pair of integrations is made with and without a Lyot depolarizer.

In the theoretical treatment of the scattering of light by a molecular atmosphere, it is more convenient to use the Stokes vector formalism to describe the polarization characteristics of the radiation field. It is possible to measure directly the Stokes parameters. Hiltner (1949, 1951, 1956) (see also Serkowzki (1962)) in the study of the polarization of starlight has used an analyzer and set it in several position angles. The intensity of light after passing through the analyzer is measured with a photomultiplier tube. From these intensities, useful relations between Stokes parameters are obtained.

The instrument described here can be used to measure the three Stokes parameters for plane polarized light. By a simple modification, it can be adopted to measure the four parameters of elliptically polarized light. In the scattering phenomena associated with sky-light, only linear polarization is encountered and there is only very little of elliptical polarization. From the Stokes parameters, the degree of polarization and the orientation of the plane of polarization can be obtained by simple calculations.

2. Theory of the Instrument

The Stokes parameters are given by (Born and Wolf, 1959)

$$\begin{aligned} s_o &= \langle a_1^2 + a_2^2 \rangle \\ s_1 &= \langle a_1^2 - a_2^2 \rangle \\ s_2 &= 2\langle a_1 a_2 \cos \delta \rangle \\ s_3 &= 2\langle a_1 a_2 \sin \delta \rangle \end{aligned} \tag{1}$$

where a_1 and a_2 are the instantaneous amplitudes of the two orthogonal components E_x and E_y of the electric vector and $\delta = \Phi_1 - \Phi_2$ their phase difference. The relation between the Stokes parameters and the elements of the coherency matrix is given by (Born and Wolf, 1959).

$$s_o = J_{xx} + J_{yy}$$

$$s_1 = J_{xx} - J_{yy}$$

$$s_2 = J_{xy} + J_{yx} \tag{2}$$

$$s_3 = i(J_{yx} - J_{xy})$$

If $I(\theta,\epsilon)$ denotes the intensity of light vibrations making an angle θ with the positive x direction when the y component is subjected to a retardation ϵ with respect to the x component, then the elements J_{ij} are given by

$$J_{xx} = I(0,0)$$

$$J_{yy} = I(90,0)$$

$$J_{xy} = \tfrac{1}{2}\left\{I(45,0) - I(135,0)\right\} + \tfrac{1}{2}i\left\{I(45,\tfrac{\pi}{2}) - I(135,\tfrac{\pi}{2})\right\} \tag{3}$$

$$J_{yx} = \tfrac{1}{2}\left\{I(45,0) - I(135,0)\right\} - \tfrac{1}{2}i\left\{I(45,\tfrac{\pi}{2}) - I(135,\tfrac{\pi}{2})\right\}$$

From (2) and (3) we have

$$
\begin{aligned}
s_o &= I(0,0) + I(90,0) \\
s_1 &= I(0,0) - I(90,0) \\
s_2 &= I(45,0) - I(135,0) \\
s_3 &= I(45,\tfrac{\pi}{2}) - I(135,\tfrac{\pi}{2})
\end{aligned} \tag{4}
$$

Making use of a polarizer oriented at different directions and a quarterwave plate to satisfy the above relations, the parameters s_o, s_1, s_2, s_3 can be determined. The degree of polarization

$$P = \frac{\sqrt{s_1^2 + s_2^2 + s_3^2}}{s_o} \tag{5}$$

The ellipticity and the orientation of the polarization ellipse are given respectively by the relations

$$\text{Sin } 2\chi = \frac{s_3}{\sqrt{s_1^2 + s_2^2 + s_3^2}} \tag{6}$$

and

$$\text{Tan } 2\psi = \frac{s_2}{s_1} \tag{7}$$

If measurements are confined to the sun vertical; i.e., the meridian plane through the sun, the degree of polarization reduces to

$$P = \frac{I(0,0) - I(90,0)}{I(0,0) + I(90,0)} \tag{8}$$

The scattered radiation can be considered as plane polarized and only s_o, s_1 and s_2 need be determined, thus eliminating the use of a quarterwave plate.

3. The Instrument

The instrument consists of four identical polarizers oriented so as to transmit light vibrations in the directions $\theta = 0^o$, 45^o, 90^o and 135^o with respect to an arbitrary direction OX. The polarizers are Glan prisms with length to aperture ration 0.85 to 1 and useable angular polarized field of 8^o at λ5893Å and 9^o at λ2000Å. Collimators designed with conventional front aperture geometry are fixed in front of each polarizer to obtain narrow beams of parallel light. An achromatic fused quartz lens was used in each collimator and a number of baffles placed beyond the focal length of the lens kept the beam divergence to a minimum. The maximum field of view of each collimator is about 3^o. The light transmitted by the polarizers pass through narrow band interference filters for selection of the spectral region and fall on the cathode of the end window type photomultiplier tube. Optional provision is made for the introduction of Lyot depolarizers in front of the photomultiplier tube window to compensate for the change in sensitivity of the cathode for differently polarized light intensity. The arrangement of the optical components in one channel is shown in Figure (1). There are four such channels in the instrument which are matched as closely as possible, except for the orientation of the polarizers. The four channels together with the associated electronic circuitry form a compact unit. A diagram of the instrument is shown in Figure (2).

It is possible to make polarization measurements in four spectral regions. This is done using narrow band interference filters. The filters are in the form of small disks of ½" diameter. The diameter is greater than what is required for covering the cross section of the light beams transversing the collimator. Sixteen filters (four for each color) are mounted symmetrically on a larger disk, so that the four identical filters in one spectral region are at equal distances from the center and on two diameters at right angles to each other. The disk is rotated through an angle of $22\frac{1}{2}^{\circ}$ to bring another set of four filters in the paths of the light beams. The rotation of the disk can be brought about in times of the order of a few milliseconds, using a Ledex digimotor switch. This is much faster than the normal scanning speed of the instrument, so that practically simultaneous measurements can be obtained in four spectral regions for any orientation of the instrument. The spectral regions selected in the present study have peak wave lengths centered at 3800Å, 4400Å, 5000Å and 5800Å with half-widths of the order of 75 to 100Å. The transmission characteristics of the various filters have been determined using Cary 14 spectrophotometer and the curves are reproduced in Figure (3).

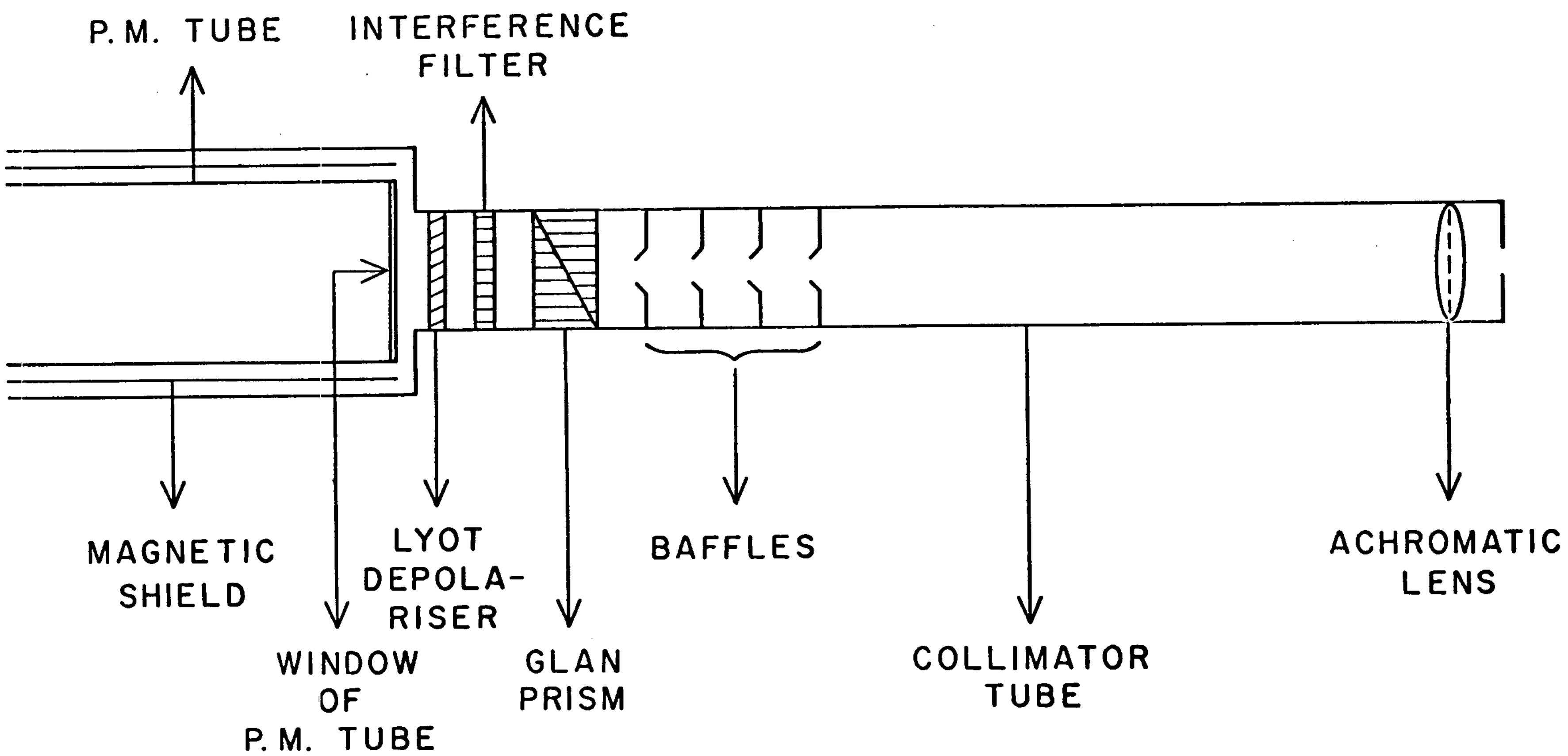

P. M. TUBE
INTERFERENCE FILTER
MAGNETIC SHIELD
WINDOW OF P. M. TUBE
LYOT DEPOLA- RISER
GLAN PRISM
BAFFLES
COLLIMATOR TUBE
ACHROMATIC LENS

Fig. 1

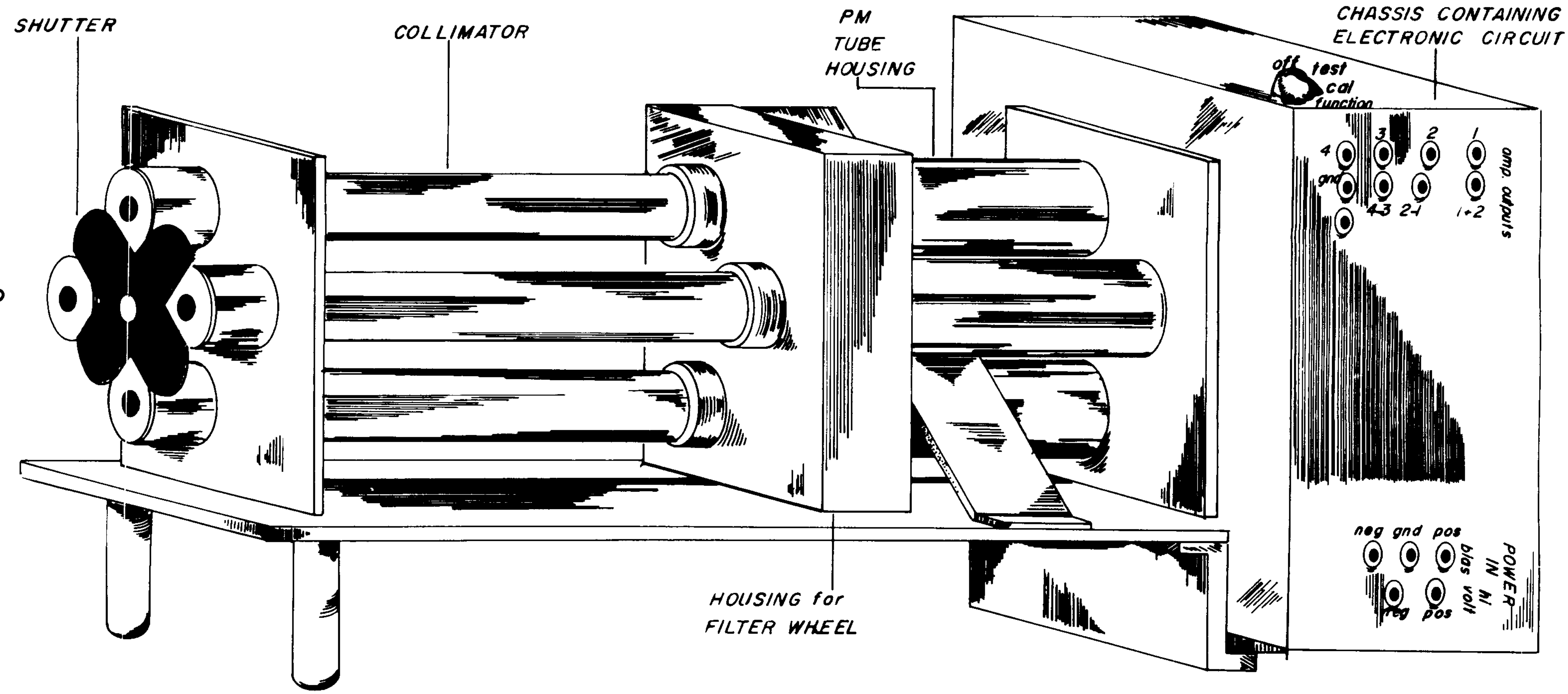

SHUTTER
COLLIMATOR
PM TUBE HOUSING
CHASSIS CONTAINING ELECTRONIC CIRCUIT
off test cal function
amp. outputs
1
2
3
4
gnd
4-3
2-1
1+2
POWER IN
neg gnd pos
bias
hi volt
neg pos
HOUSING for FILTER WHEEL

Fig. 2

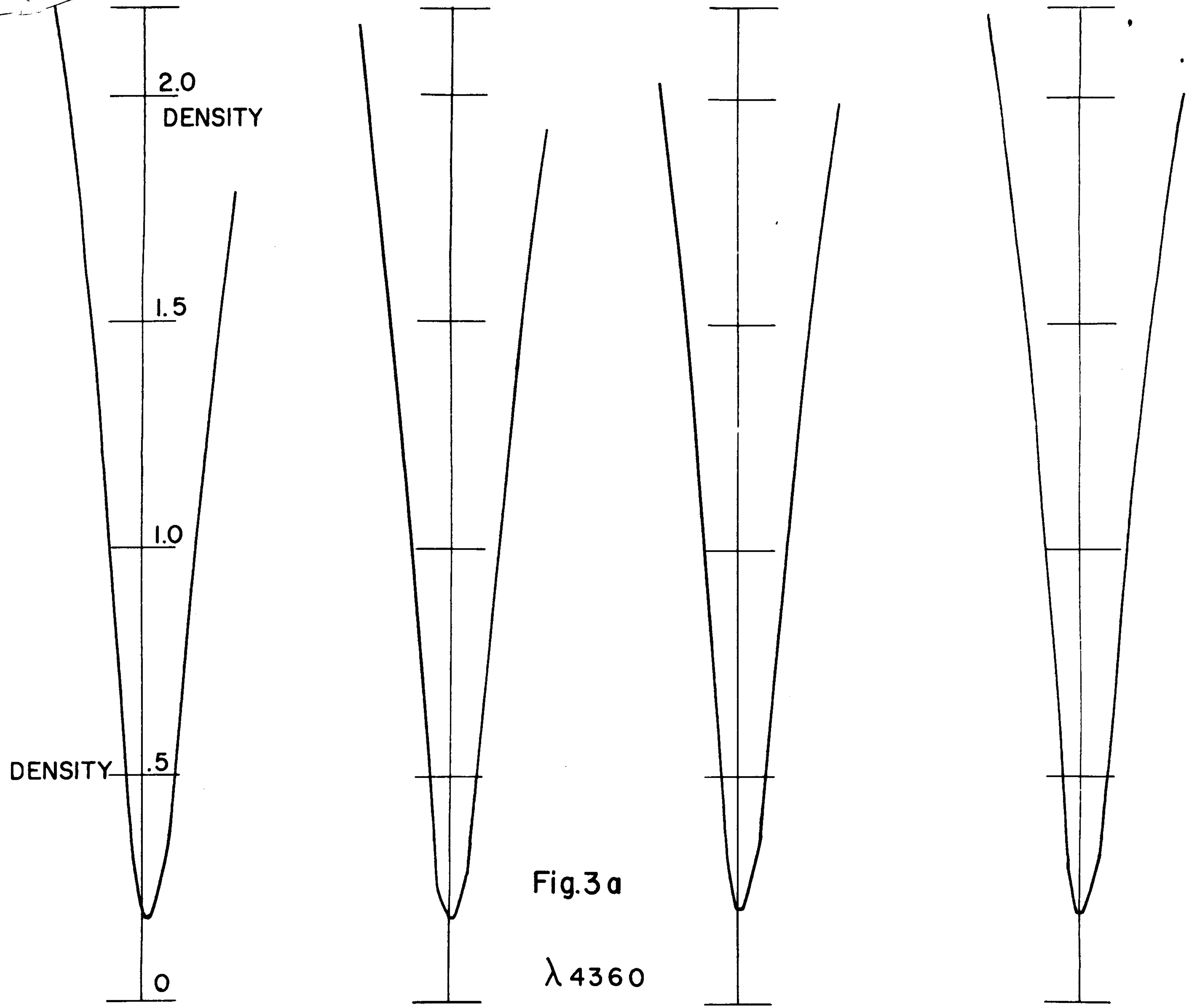
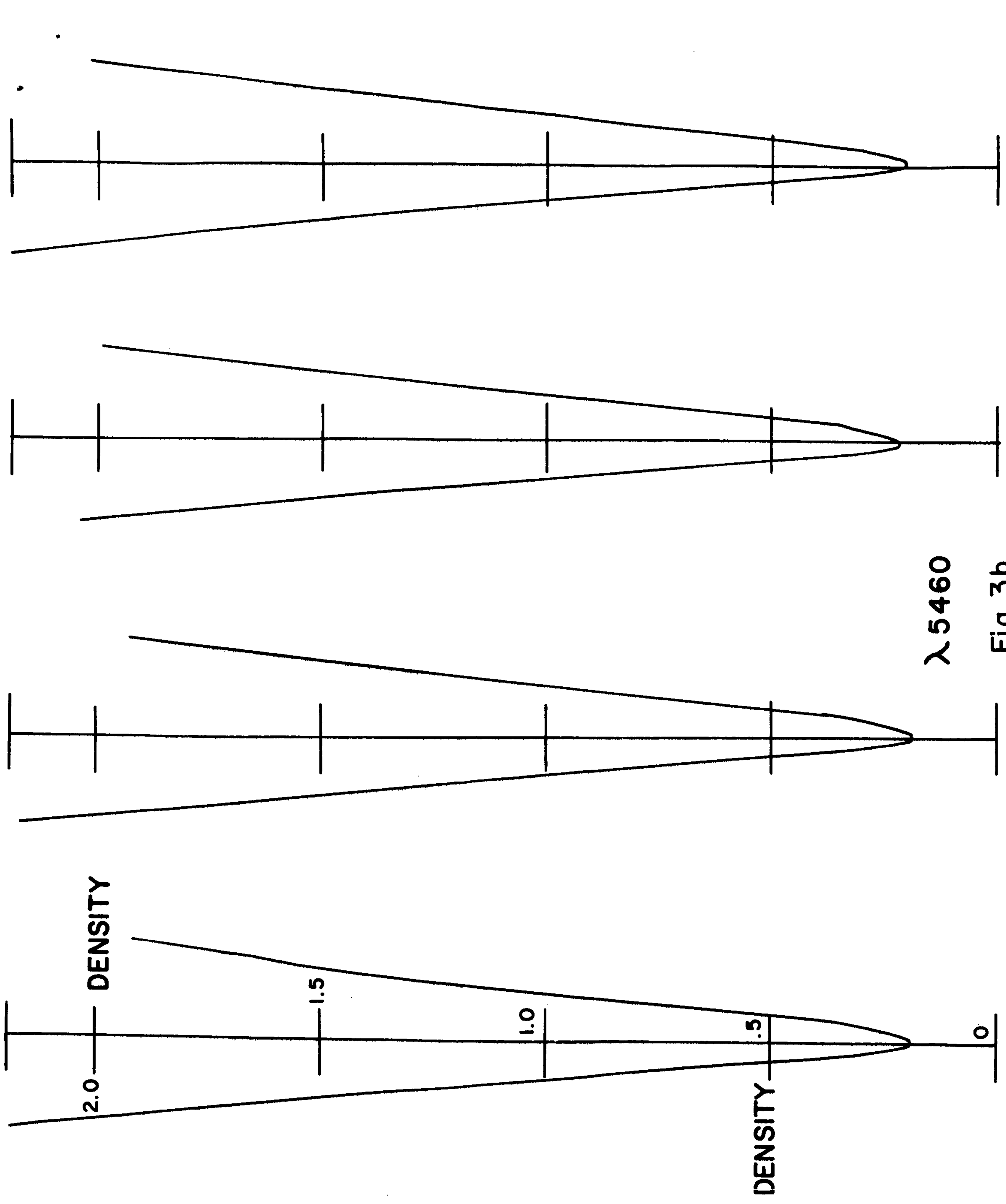


Fig. 3a

λ 4360



λ5460

Fig. 3b

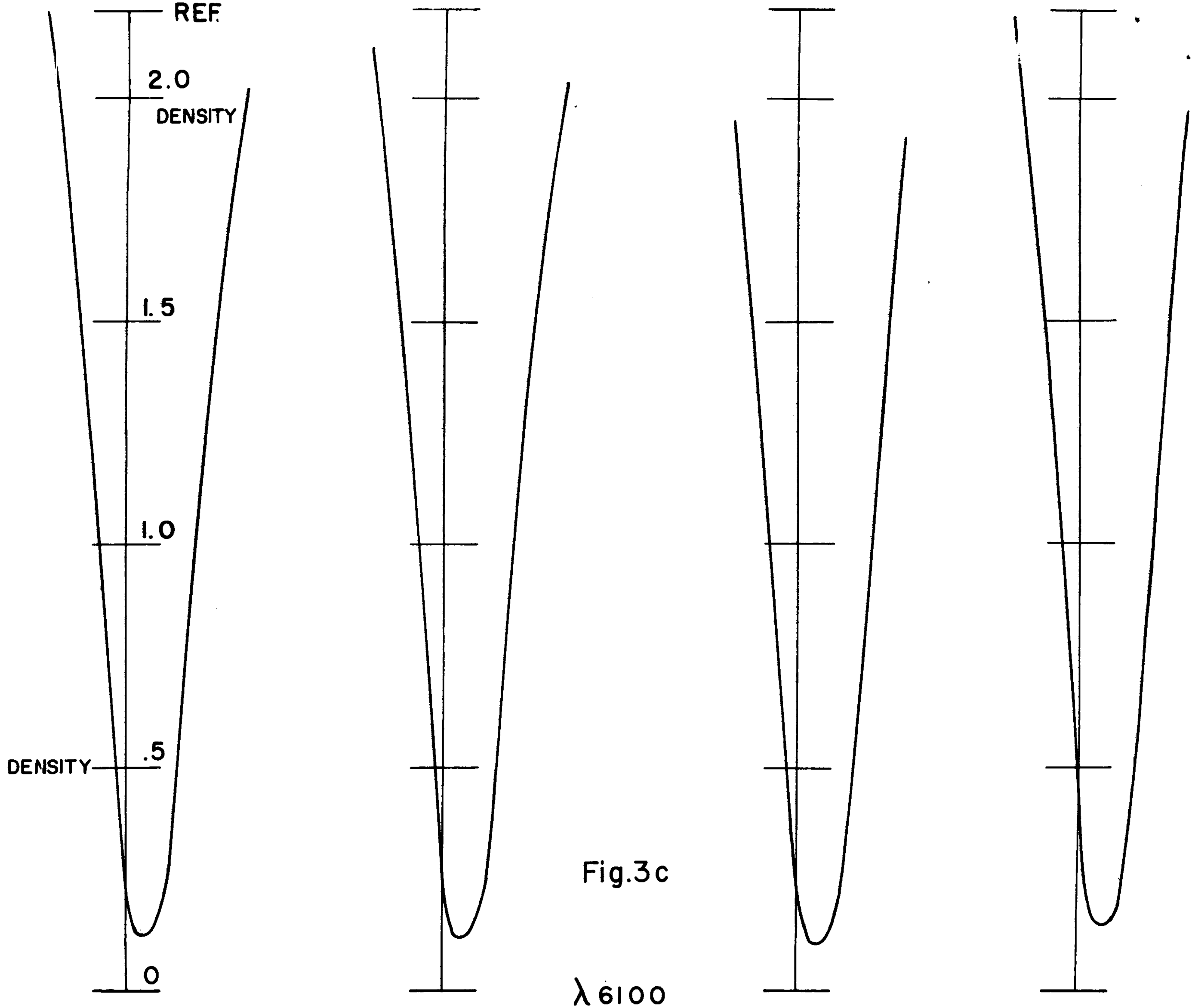


Fig.3c

λ 6100

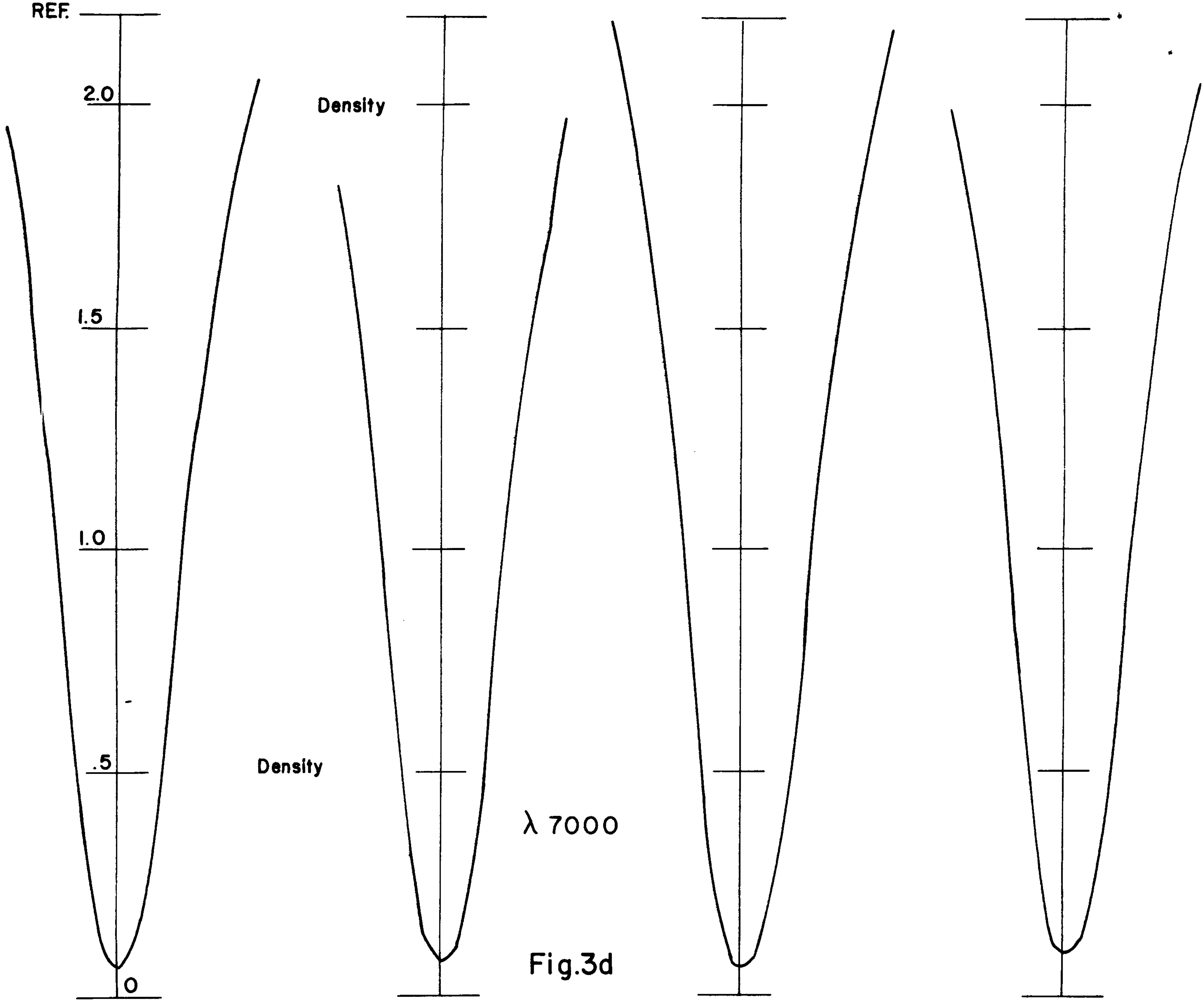


Fig.3d

The photomultiplier tubes have S-11 spectral response and they are selected from a large number to have closely matched characteristics. A potentiometer is included in the voltage divider network of each tube to adjust the gain (Figure (4)). In addition to four individual output signals from the photomultiplier tubes, the sum and differences according to relation 4 are also obtained using high-quality d.c. operational amplifiers. The d.c. amplifiers (Nexus CDA-3a) used are quite stable and the errors introduced by the process of addition and subtraction at low signal levels are negligible. Provision is made to check the performance of the operational amplifiers by feeding calibrated signals. The detailed circuit diagram used is shown in Figure (5).

4. Calibration

Before making any measurements with the instrument, the four channels should be matched closely within limits of allowable error. A standard light source (Photo Research Corp., No. 1656) was used for initial photometric calibration. The source contains a quartz iodide lamp. With a 6" diameter, spherical housing, even luminance is obtained at the 2" diameter opening. Different brightness settings can be obtained by means of a micrometer adjustment, without changing the color temperature of the lamp. The lamp is always run with a current regulated power supply with regulation better than required for maintaining constant brightness. The standard source is mounted on a frame capable of horizontal and vertical transverse of more than 4". The instrument is placed on a rigid table and after proper

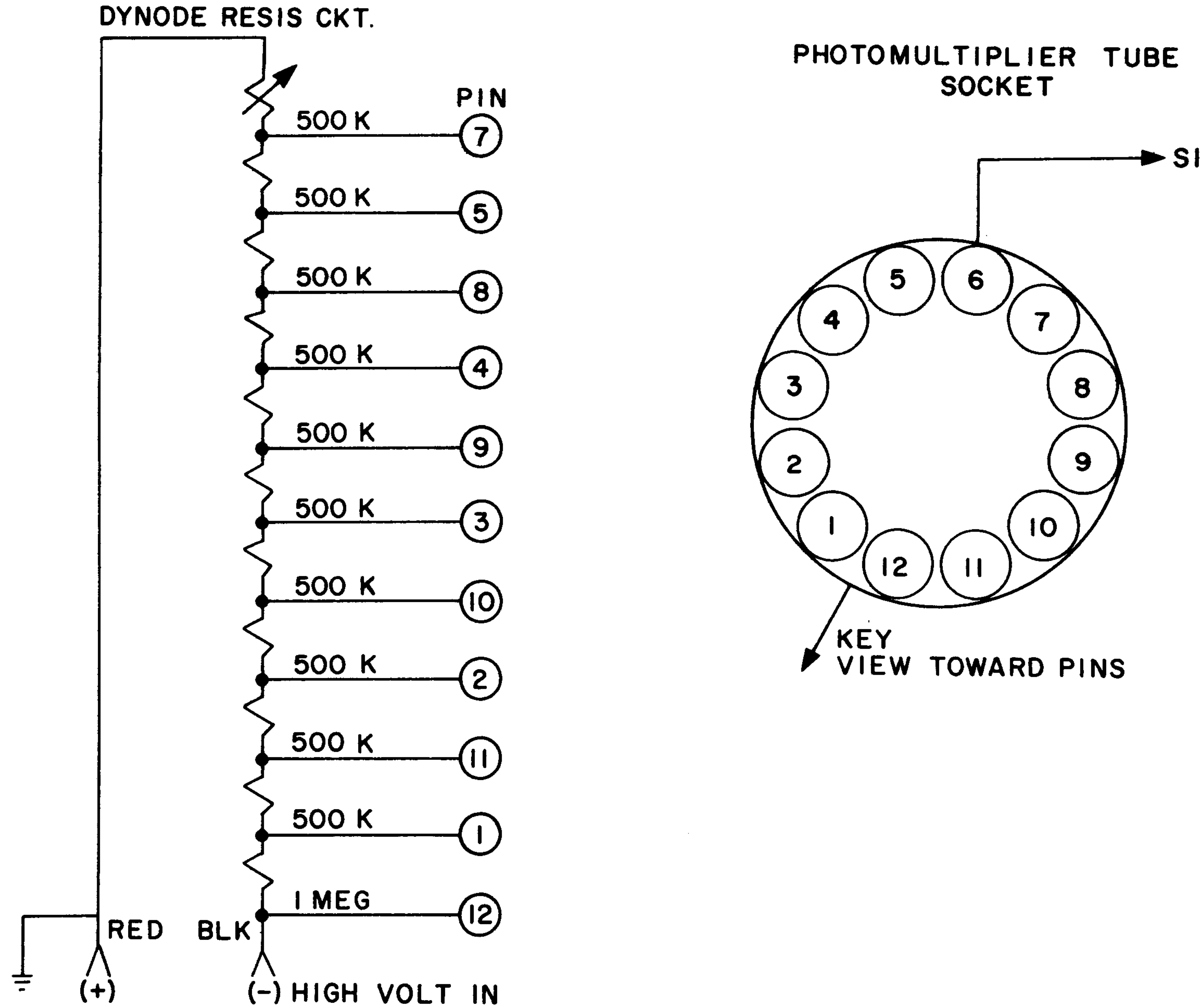
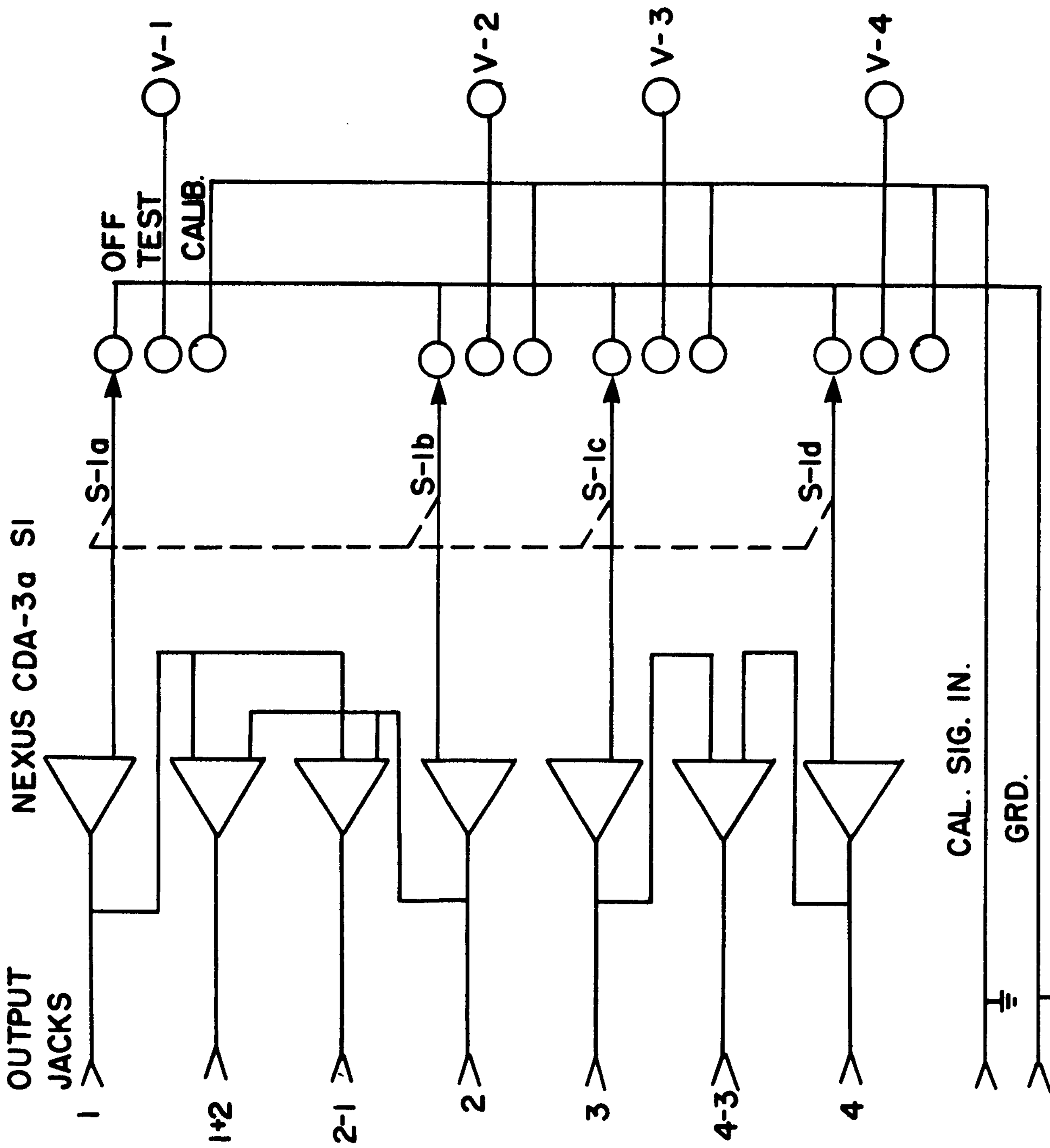
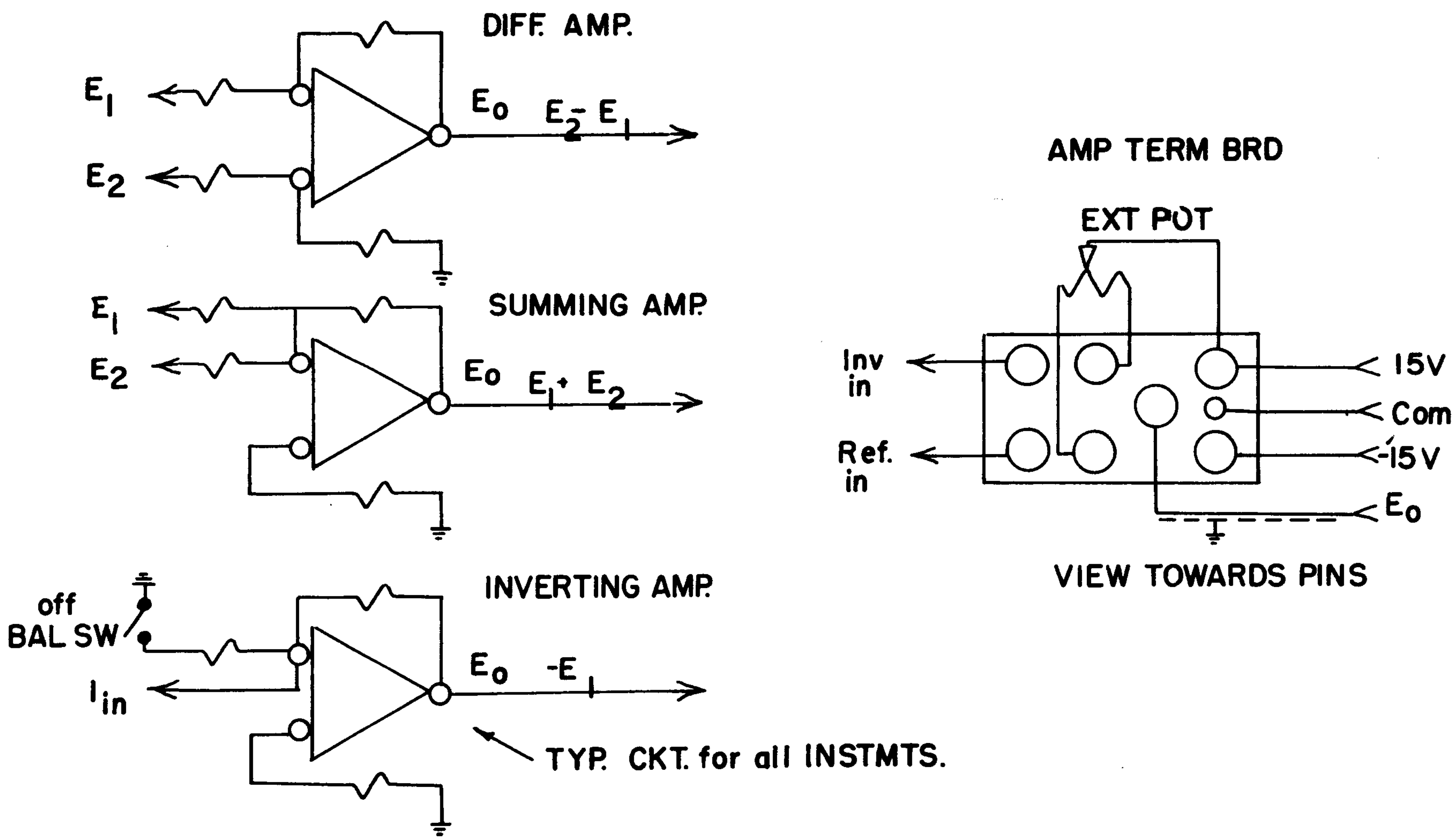

DYNODE RESIS CKT.
PIN
500 K
500 K
500 K
500 K
500 K
500 K
500 K
500 K
500 K
500 K
I MEG
7
5
8
4
9
3
10
2
11
1
12
RED
BLK
(+)
(-) HIGH VOLT IN
PHOTOMULTIPLIER TUBE
SOCKET
SI
KEY
VIEW TOWARD PINS

Fig. 4



OUTPUT JACKS
NEXUS CDA-3a SI
1
1+2
2-1
2
3
4-3
4
S-1a
S-1b
S-1c
S-1d
OFF
TEST
CALIB.
V-1
V-2
V-3
V-4
CAL. SIG. IN.
GRD.

Fig. 5a



NOTE: ALL AMP. ARE NEXUS CDA-3a

Fig. 5b

alignment, the source is moved till the center of the opening is against the aperture of the individual channels. The gain of the photomultiplier tubes are adjusted using the potentiometer in the voltage divider chains to get equal outputs. The outputs are measured with a digital voltmeter correct to a millivolt.

For polarization calibration, a simple device based on the principle of polarization by reflection was constructed and used. This consists of four right angle prisms of fused quartz fixed to a framework in such a way that they can be simultaneously rotated by small amounts with a gear mechanism. The hypotenuse surfaces reflect unpolarized sunlight and, after attenuation by neutral density filters, enter the collimator tubes along their axes. The degree of polarization of the reflected light can be calculated in terms of the angle of incidence θ and the refractive index of the prism material m.

$$P_R = \frac{2\mu\ (1 - \mu^2)\ \ (m^2 - 1 + \mu^2)^{\frac{1}{2}}}{\mu^2\ (m^2 - 1 + \mu^2)\ + \ (1 - \mu^2)^{\ 2}}$$

The angle of incidence can be varied to get a number of values of polarization to calibrate the instrument. The arrangement of the prisms, the gear mechanism to turn them, and the scale to read the angle of rotation are illustrated in Figure (6). The unit can be attached to the main instrument whenever desired and all stray light avoided by means of a light-weight enclosure.

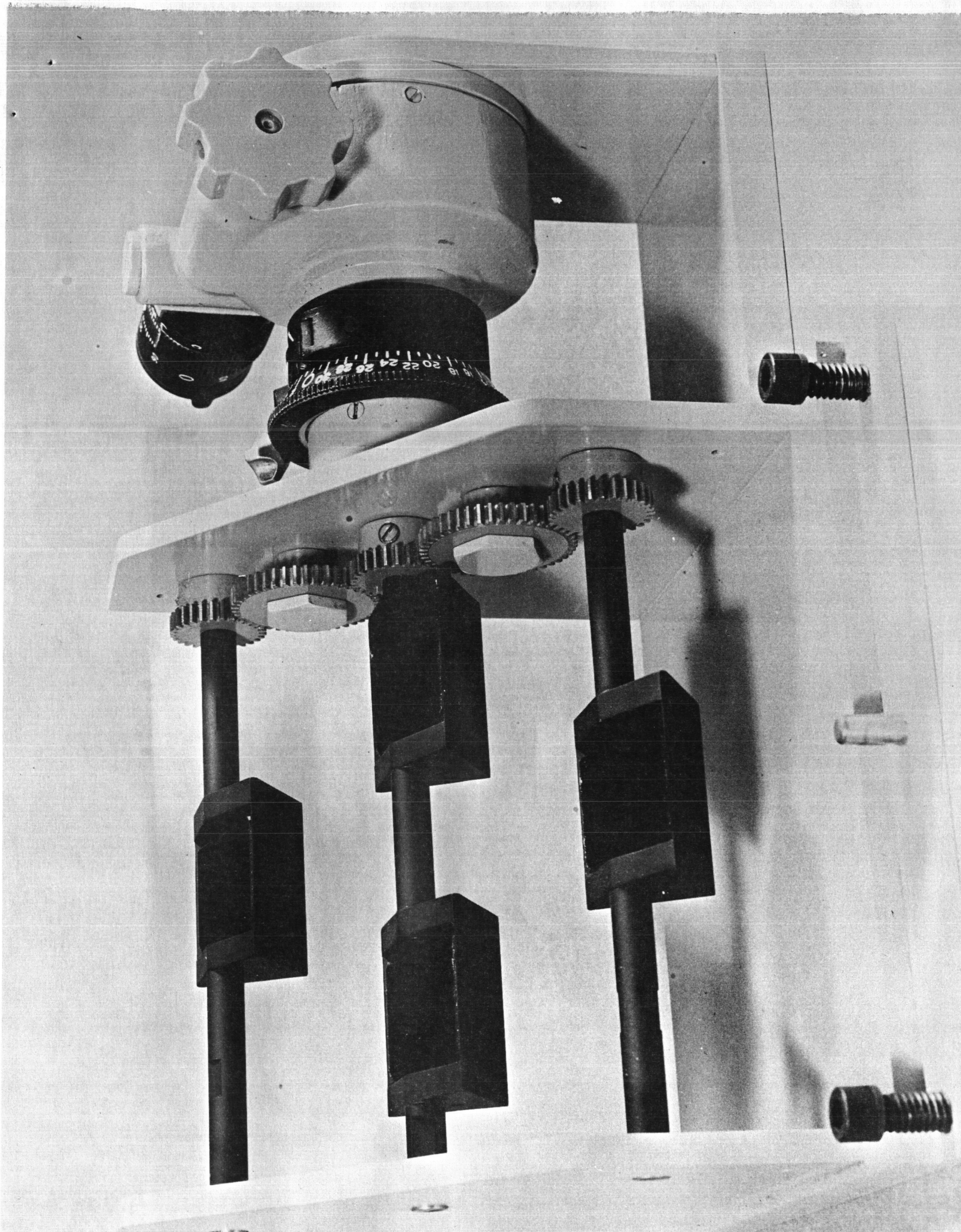


Fig. 6

5. Other Features

As mentioned earlier, the polarimeter is primarily designed as a laboratory model to serve as a basis for the development of a satellite-borne instrument. Since preliminary ground-based measurements are required to be carried out to test the performance of the instrument, some additional features, such as scanning mechanism, sunfollower assembly, etc., have to be designed and integrated to the instrument setup.

6. Scanning Mechanism

The instrument is fixed to the shaft of an equatorial mount and is turned with a motor to scan the sky from horizon to horizon in about five minutes. At the end of each scan, the direction of motion is reversed automatically, using a mercury switch and a relay. The angular position of the instrument can be either read out on a scale fixed to the shaft or may be recorded continuously as an analog voltage from a ten-turn precision potentiometer. The azimuth angle can be measured from a compass fixed in a convenient place on the equatorial mount. The direction of scan can be reversed from any angular position of the instrument by means of a separate reversing switch. A diagram of the instrument fixed to the shaft and the mechanical arrangements used are shown in Figure (7).

During each scan made in the principal plane of the sun, the instrument will be directly pointed to the sun. It is necessary to prevent solar radiation entering the instrument and damaging the

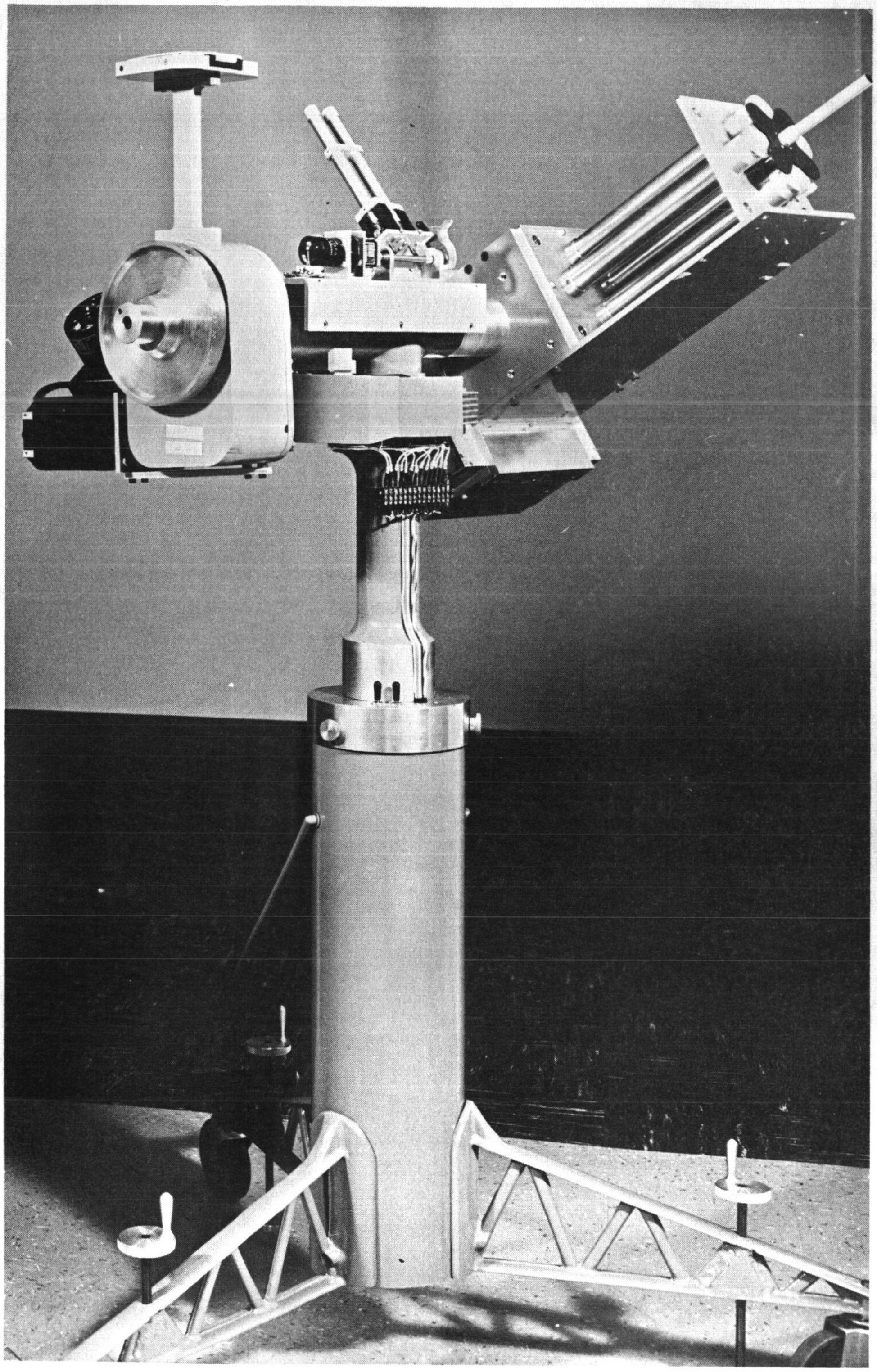


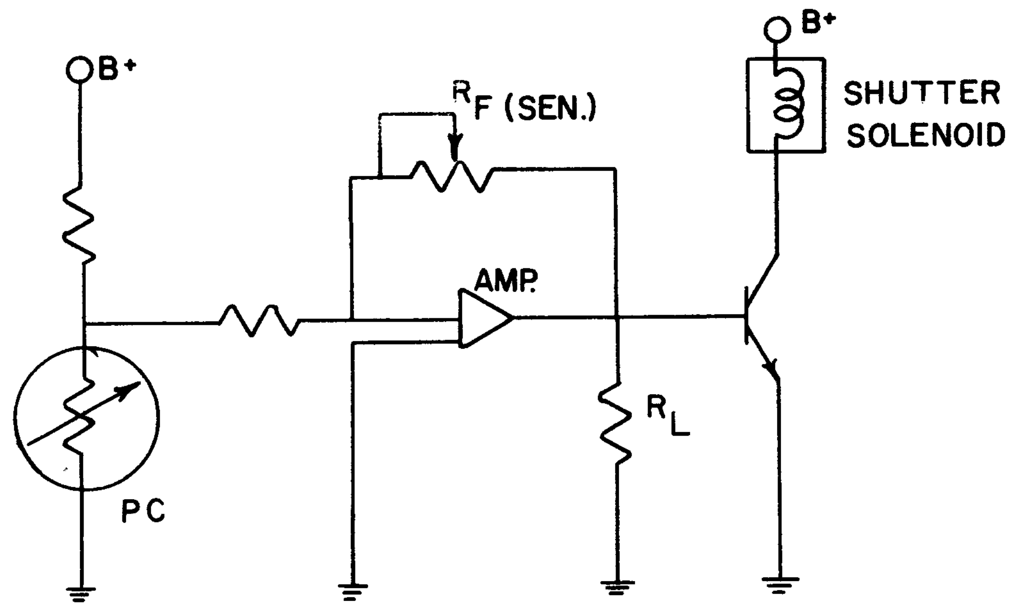
Fig. 7

photomultiplier tubes. This is done in a simple manner by using a shutter which is actuated by a solenoid which, in turn, is energized by a photoconductive cell. The photoconductive cell is fixed to one end of a tube about 5" long and ½" in diameter. Vanes are fixed to the tube so that when the solenoid is energized, they take up positions against the collimator apertures, thus blocking direct sunlight from entering the instrument. By a simple circuit (Figure (8)), it is possible to adjust the closest angle to the sun at which the shutter should be actuated.

7. <u>Sunfollower Assembly</u>

During the ground-based observations, the instrument is made to scan the sky in the sun vertical; i.e., the meridan plane through the sun. To maintain the instrument in the sun vertical, a servo-controlled sunfollower assembly was designed and constructed. Vasilev and Shapov (1963) have described a solar tracking head used in conjunction with a difraction grating spectrometer. Their sensing unit consisted mainly of an anti-dazzle shield fixed on a strut above a pair of photoconductors. The shield casts shadows to the same extent on each of the photoconductors. A slight change in the shadow of one of them can generate an error signal. Two pairs of photoconductors are used to correct longitudinal and transverse deviations. The device described here also makes use of photoconductors and the shadowing principle, but the arrangements are different.

A dual element photoconductive cell is mounted at one end of a metal tube, 6" long and 1/2" in diameter. The metal tube,



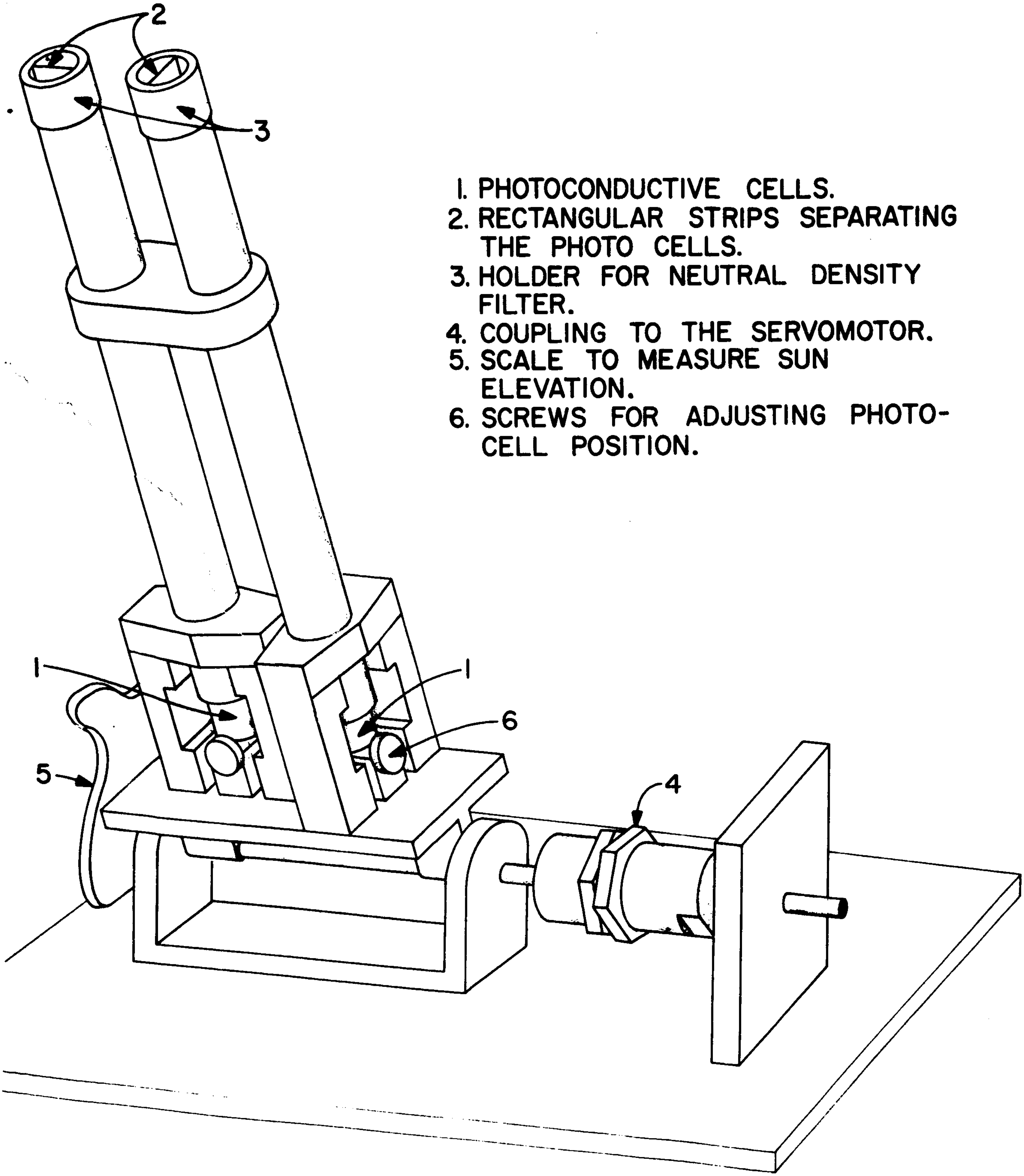
SHUTTER AMP. CKT.

Fig. 8

blackened inside, is divided in two sections along its length by a thin strip of metal in such a way that the two elements fall on either side of the strip. When the tube is directed toward a distant source of light, the two elements will be uniformly illuminated and can be adjusted to have the same effective resistance. When the orientation of the tube with respect to the source is slightly changed, there will result a difference in illumination of the two elements. This effect can be used to generate an error signal to actuate a servo mechanism for the necessary control and correction. A picture of the tracking head is shown in Figure (9).

Two tubes, each carrying a dual element photoconductive cell, are mounted side by side to a common frame which is coupled to the shaft of a servo motor. The cells are mounted in such a way that the planes of the strip separating them are perpendicular to each other. The error signal from one of the cells actuates a servo mechanism to keep the tubes always pointed to the sun, while the error signal from the second actuates a second servo system to orient the instrument in the sun vertical. The servo system which orients the instrument in the sun vertical is attached to a vertical shaft inside the tubular support.

The two separate servo systems are practically identical in all respects, except for the fact that one of them has to turn a heavier load and, so, has to be designed accordingly. A block diagram of the servo system is shown in Figure (10) and a detailed circuit diagram in Figure (11). The sensors are Clairex dual element photoconductive cells, carefully selected to have matched normal resistance



1. PHOTOCONDUCTIVE CELLS.
2. RECTANGULAR STRIPS SEPARATING THE PHOTO CELLS.
3. HOLDER FOR NEUTRAL DENSITY FILTER.
4. COUPLING TO THE SERVOMOTOR.
5. SCALE TO MEASURE SUN ELEVATION.
6. SCREWS FOR ADJUSTING PHOTO-CELL POSITION.

Fig. 9

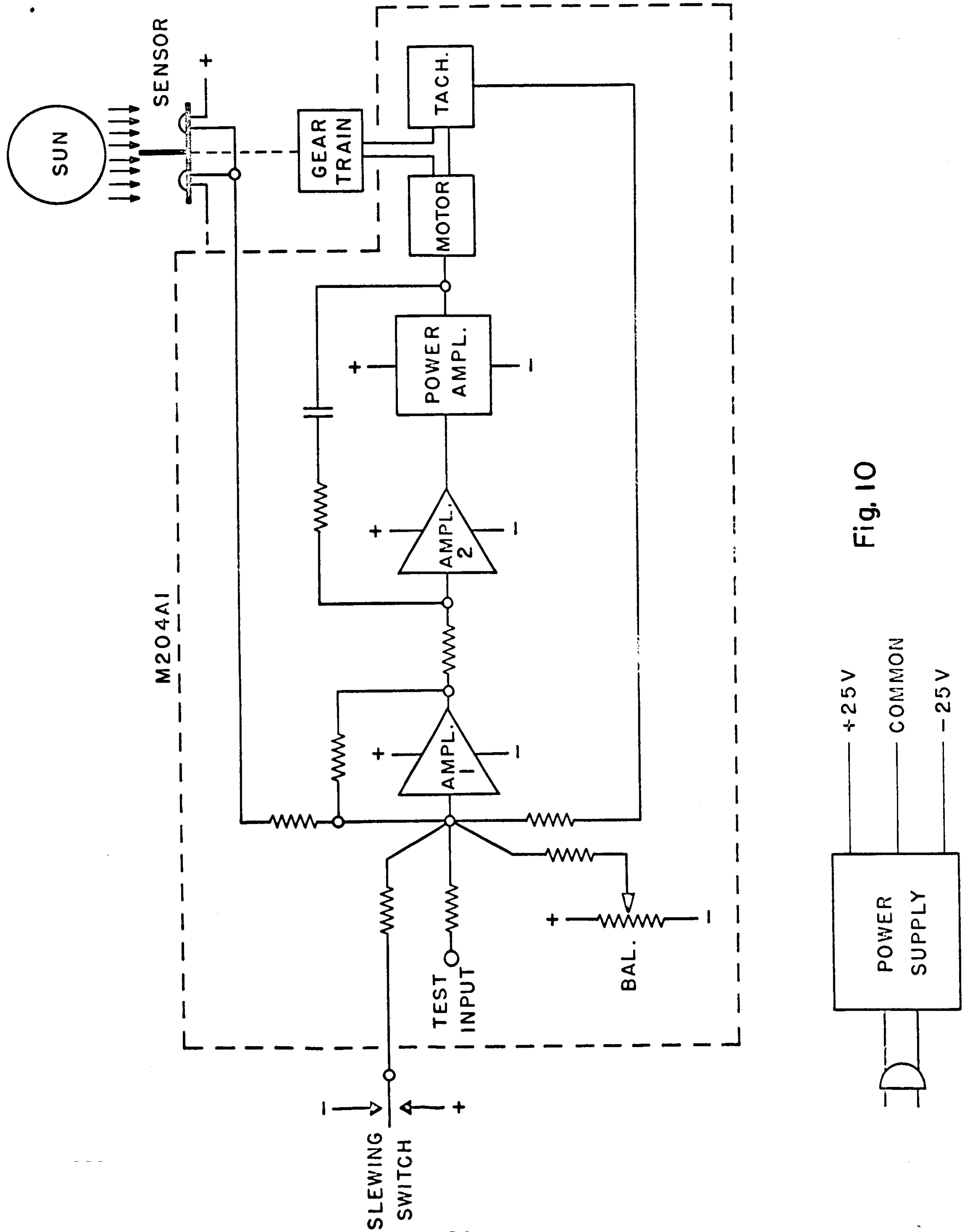

SUN
SENSOR
+
GEAR TRAIN
TACH.
MOTOR
POWER AMPL.
AMPL. 2
AMPL. 1
M204A1
TEST INPUT
BAL.
SLEWING SWITCH
+25V
COMMON
-25V
POWER SUPPLY

Fig. 10

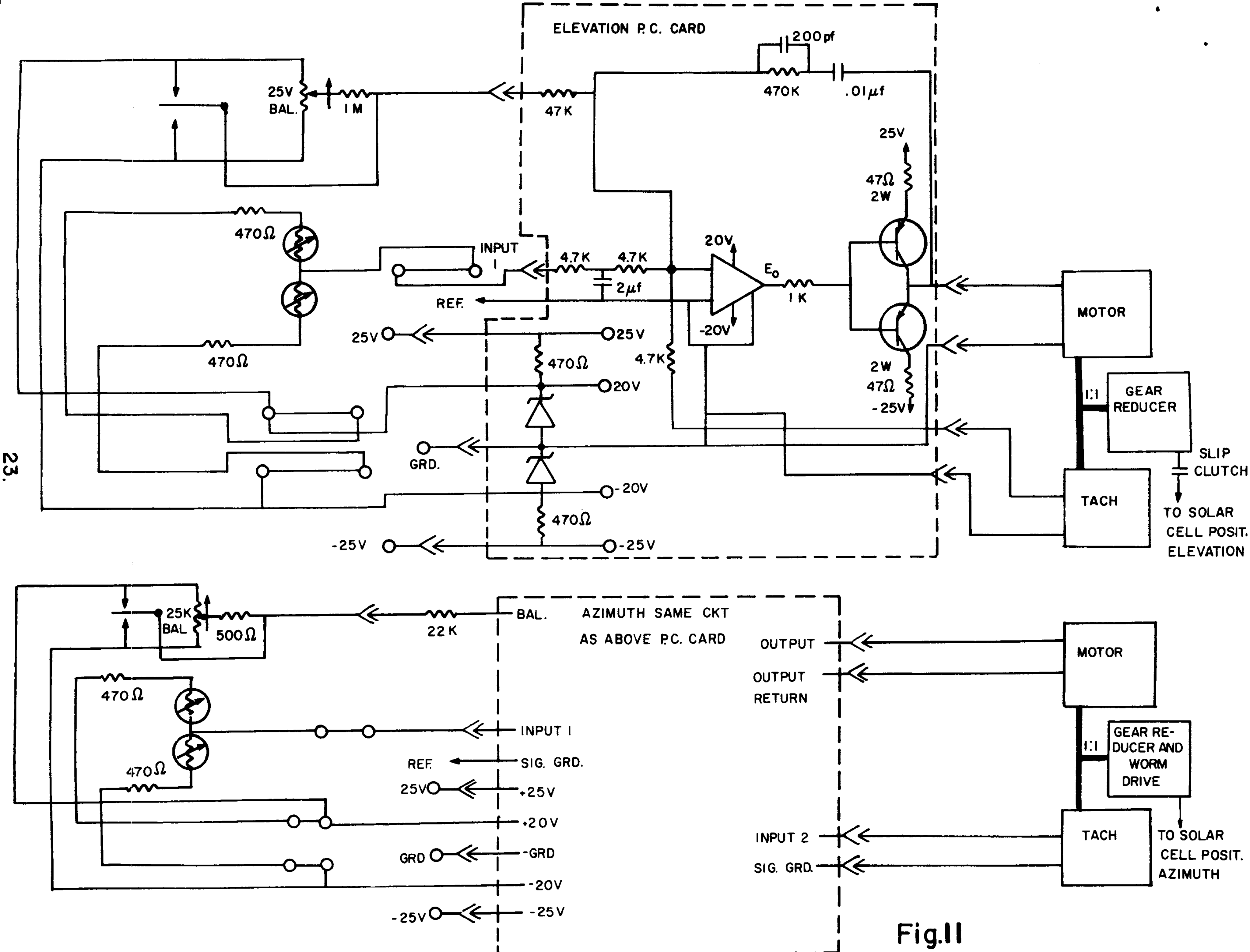

ELEVATION P.C. CARD
200pf
470K
.01μf
47K
25V
BAL.
1M
25V
47Ω
2W
470Ω
INPUT
1
4.7K
4.7K
2μf
20V
E0
1K
REF.
-20V
25V
25V
470Ω
4.7K
2W
47Ω
-25V
20V
MOTOR
1:1
GEAR
REDUCER
GRD.
SLIP
CLUTCH
-20V
TACH
TO SOLAR
CELL POSIT.
ELEVATION
470Ω
-25V
-25V
25K
BAL
500Ω
22K
BAL.
AZIMUTH SAME CKT
AS ABOVE P.C. CARD
OUTPUT
OUTPUT
RETURN
MOTOR
470Ω
INPUT 1
REF.
SIG. GRD.
GEAR RE-
DUCER AND
WORM
DRIVE
25V
+25V
+20V
GRD
-GRD
INPUT 2
SIG. GRD.
TACH
TO SOLAR
CELL POSIT.
AZIMUTH
-20V
-25V
-25V

Fig.11

of 7.5K Ohms. The velocity servos with the tachometer feedback are designed specifically for smooth controlled low-speed operation. Though the response required is not fast, it has to be quite smooth. The system error is not allowed to become large before applying correction. The sensitivity is increased by using a preamplifier which, in the present case, is an Opamp Model 4009, with additional Zener stabilization of the input voltage of ± 24 V. The motors are Inland TO 716A and the tachos are Servo Tek SB 740A.7. Gear speed reducers are used to get the required response speed. Each servo system is a complete closed inner loop unit and can be operated independent of light sensors for separate slewing and switching. To prevent saturation of the photoconducting elements when exposed to direct sunlight, neutral density filters are used and the attenuation is adjusted to get the maximum sensitivity. The cells can easily be replaced should they deteriorate after continuous use. The elevation of the sun at any instant can be obtained by a scale fixed to the sunfollower assembly. A slip ring is used between the sensor and the servo system within the tubular support to prevent twisting of the wires when the instrument is turned for orientation in the sun vertical.

8. Data Handling System

The main data from the instrument are either the individual outputs of the four photomultiplier tubes or the sum and differences as indicated in the equation (4). These data can be recorded in a four-channel pen recorder (Texas Instruments Servo Riter II).

The auxiliary data, such as the zenith angle of the sun, the azimuth angle, the orientation of the instrument, the spectral region under investigation, the general condition of the sky, etc., are noted separately on the record paper for identification. The angular position of the instrument can be recorded directly when the sum and differences are recorded. It is also possible using a simple control switch to read all the output voltages sequentially on a digital voltmeter correct to a millivolt.

The polarimeter setup for scanning the sky and the control panel are shown in Figure (12). A Cicoil Superflex cable with 20 conductors (10 with shields) is used to connect the instrument to the control panel. Normally, measurements are made only on days with clear sky from the terrace of the sixth floor of the building. The measurements will, of course, be made under a variety of sky conditions and from different locations after completing the calibration of the instrument in a satisfactory manner.

The main problem connected with the instrument described above is associated with the multi-sensor system. Photomultiplier tubes generally show some slight amount of drift, even if they are controlled very precisely. The over-all accuracy that can be obtained with the instrument primarily depends on the matching of the optical components as well as the photomultiplier tube characteristics. By very careful selection of the components and control of the gain of the photomultiplier tubes, it is possible to attain an accuracy of 3% in the measurements of the individual outputs.

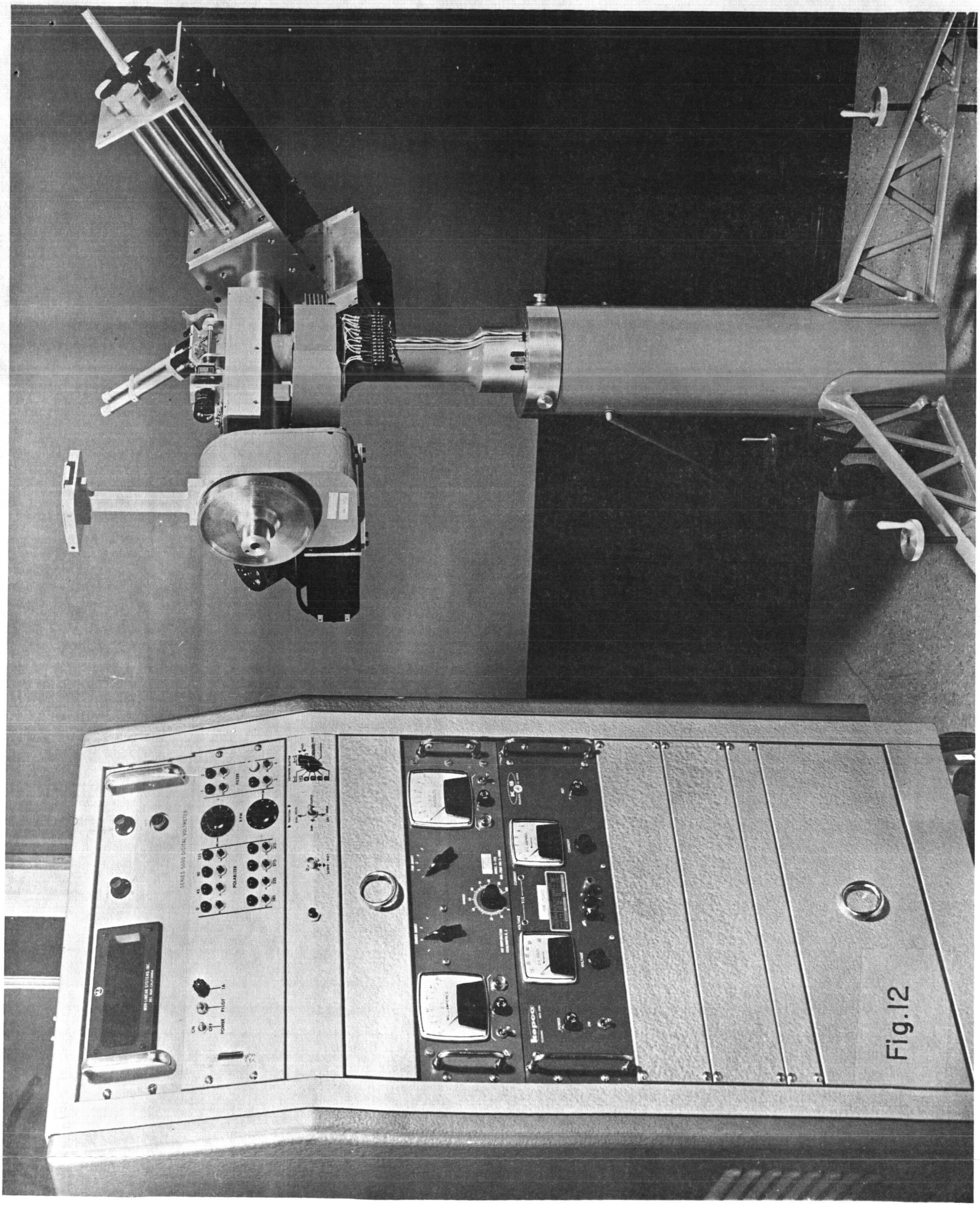


Fig.12

9. <u>The Rotating Prism Polarimeter</u>

An auxiliary instrument containing a rotating polarizer has been constructed for comparison purposes to ascertain the amount of variation in the measured quantities merely due to the difference in the sensor characteristics. The instrument consists of a single collimator and a Glan prism polarizer mounted at the center of a circular scale. The prism can be rotated by means of a Globe d.c. motor and the amount of rotation measured on the circular scale. A filter wheel carrying four narrow band interference filters is attached to a second Globe d.c. motor to bring the desired filter in the path of the light beam. A single photomultiplier tube detects the light passing through the instrument. The photomultiplier tube and the associated electronic circuit are the same as in the four channel instrument. Using multi-deck rotary switches and micro-switch relays, it is possible to stop the motor when the position of the polarizing prism transmits light vibrations having directions $\theta = 0^{o}$, 45^{o}, 90^{o}, 135^{o}, 180^{o}, 225^{o}, 270^{o} and 315^{o} with respect to a reference direction, say the horizontal. The desired angle can be selected by push button switches fixed on the control panel. The color filter selection can also be made in a similar manner. Minature lamps (of the appropriate color in the case of the filters) are turned on when the rotation of the prism or the filter wheel is completed through the appropriate angle. A diagram illustrating the arrangement of the various components in the rotating prism polarimeter is shown in Figure (13).

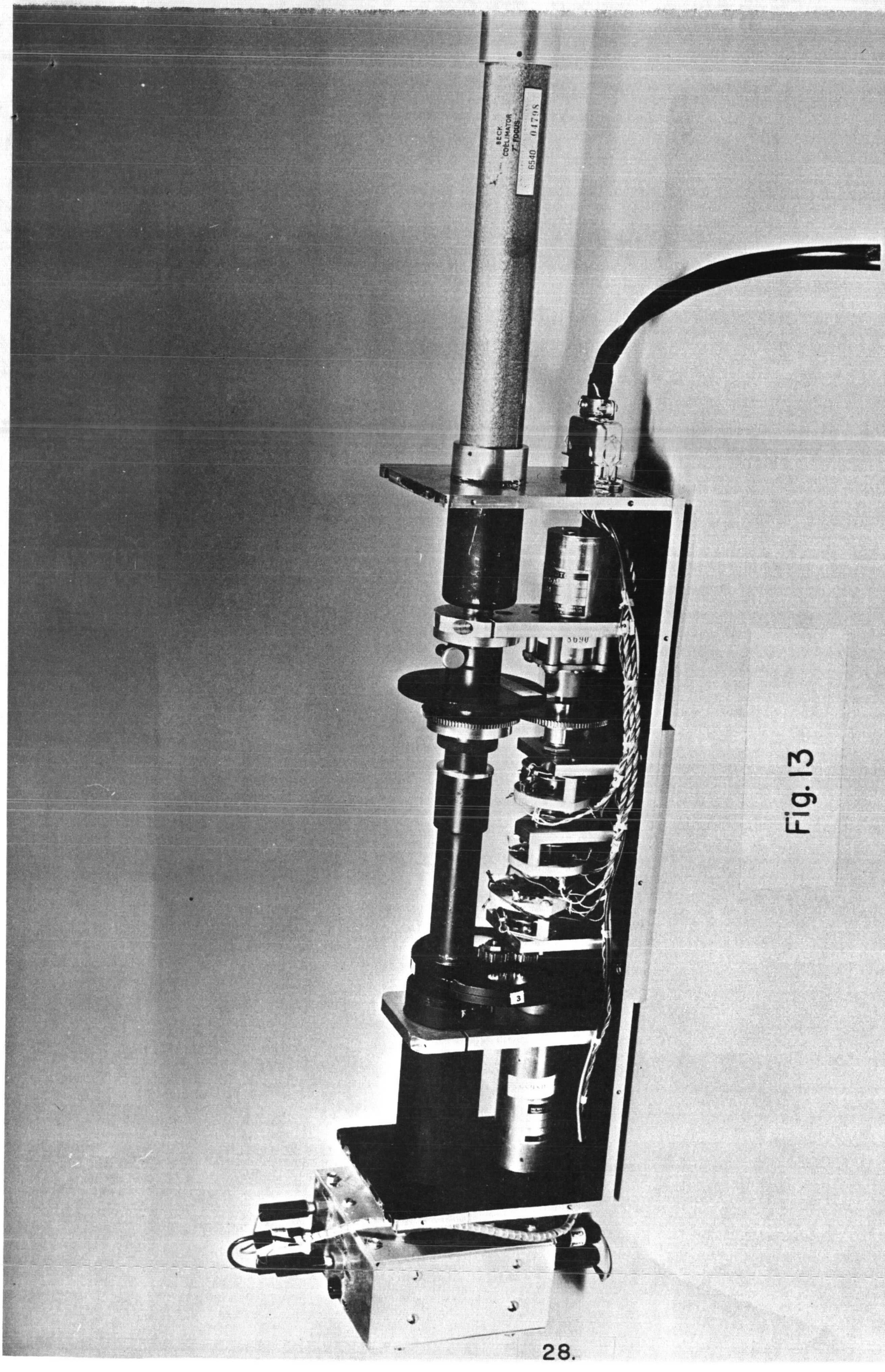


Fig. 13

The instrument is a very compact one and can be fixed to the other end of the same shaft of the equatorial mount carrying the four-channel instrument. This enables simultaneous measurements to be made with both the instruments under the same conditions. The output of the photomultiplier tube can be read out on a digital voltmeter in sequence when the polarizing prism is turned to the various positions. The prism can also be rotated continuously at various speeds up to 20 RPM, and the data recorded on a Baush and Lomb VOM-7 pen recorder with the even marker connected to indicate the various positions of the prism at intervals of 45 degrees. The detailed circuit diagram showing the operation of the switches and relays and the control panel is shown in Figure (14).

The rotating prism polarimeter is also calibrated with the standard light source. Under the ideal condition that the light from the standard source is unpolarized, the output of the photomultiplier tube is expected to be constant as the prism is rotated. This is found to be very nearly true. The slight differences observed may be either due to the slight polarization of the light coming out of the standard source or due to the difference in the sensitivity of the photomultiplier tube for different vibration directions in the light beam. A polarizer is fixed in front of the collimator and the prism in the instrument is rotated to verify that the output follows the $\cos^2 \theta$ curve within the limits of experimental error.

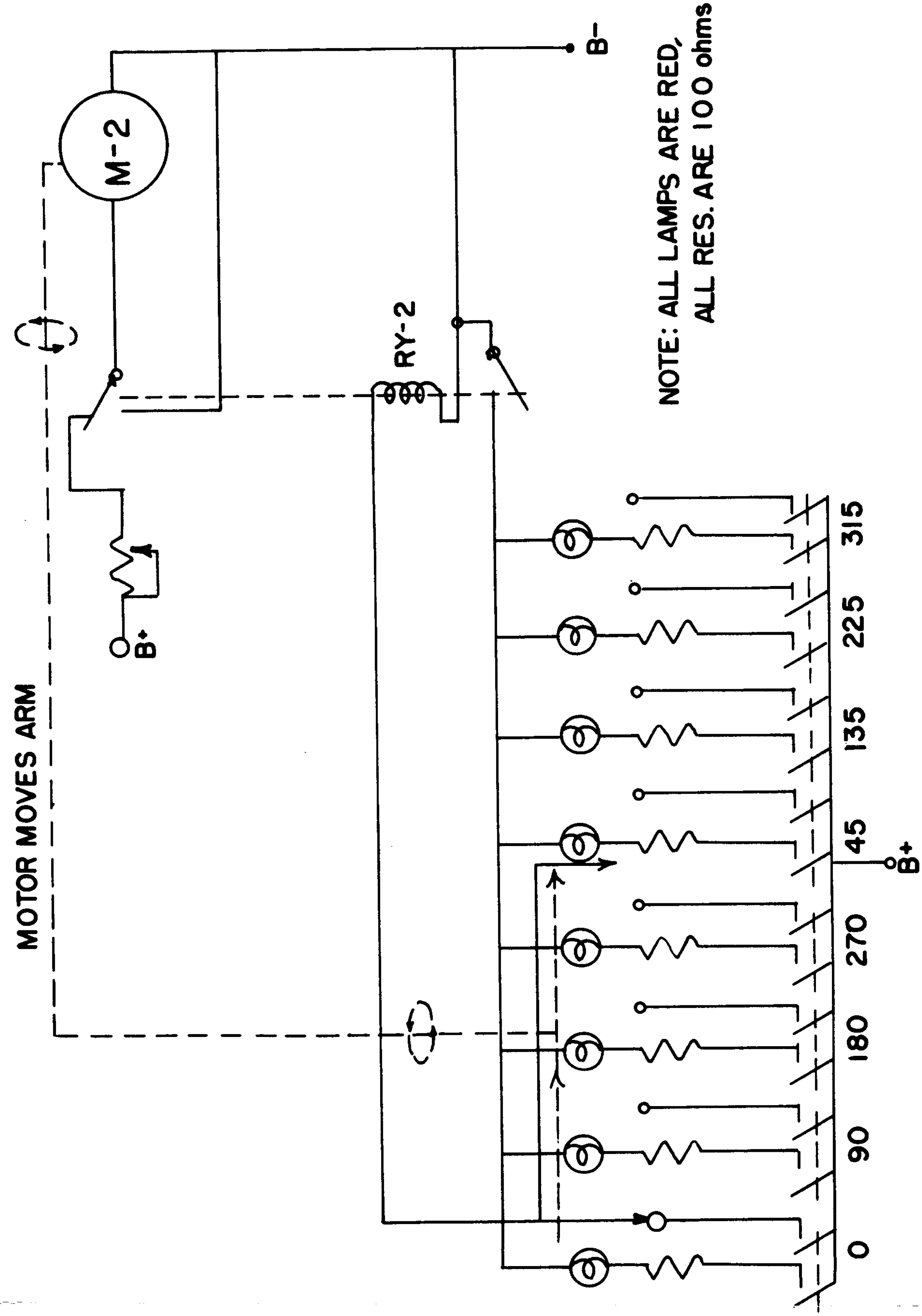

MOTOR MOVES ARM
M-2
B-
B+
RY-2
NOTE: ALL LAMPS ARE RED,
ALL RES. ARE 100 ohms
0
90
180
270
45
135
225
315
B+

Fig. 14a

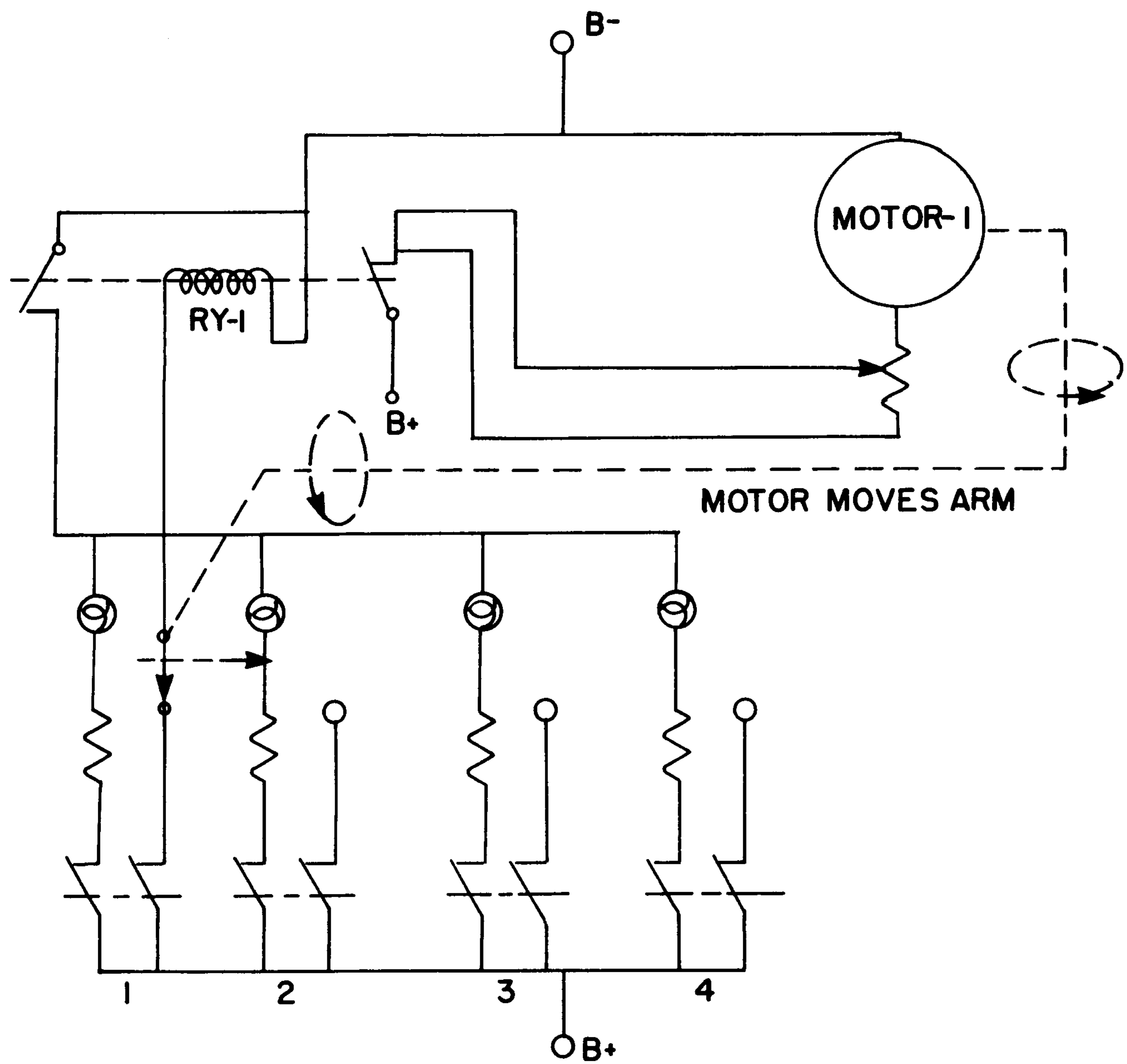


Fig. 14b

10. General Remarks

In the case of measurements of skylight polarization from a fixed platform on the ground, it is possible to have rotating components in the instrument, like a rotating analyzer or a rotating retardation plate. The spectral filters can be changed at the end of each scan without losing much resolution. Since measurements are made by pointing the instrument up towards the sky, variations in the ground reflectance do not affect the results very much.

The conditions are quite different when measurements are made from high altitude by pointing the instrument towards the earth and also from a moving platform. Variations in the ground reflectance will be more rapid. Clouds and shadows will intercept the field of view of the instrument. In order to obtain an accuracy of 1% or better, the data rate will have to be extremely high which may not be always practical. In the system described here with fixed polarizers and having no moving components, the restriction on data rate is not so severe. The cost of construction of hardware for flight applications will be much less if there are no moving elements. The instrument with only passive elements can be considered as more reliable than one with moving elements. If the polarization in different spectral regions are measured in parallel using separate sets of light sensors for each, then there is no need for providing separate redundancy of data. These are some of the main advantages in a simple design of this type, especially for spacecraft applications.

The main disadvantages, as mentioned earlier, are the drift in the light sensors and the difficulty of calibrating the system on the ground as well as during flight. These problem areas are being looked into in more detail and will be discussed in later reports.

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12. References

Born, M. and E. Wolf	Principles of Optics, Pergamon Press, London, 1959.
Bullrich, K.	Advan. Geophys. 10, 108-259, 1964.
Gehrels, T. and T. Teska	Appl. Opt. 2, 67, 1963.
Hiltner, W. A.	Astrophys. J. 109, 471, 1949.
Hiltner, W. A.	Astrophys. J. 114, 241, 1951.
Hiltner, W. A.	Astrophys. J. Suppl. Ser. 2, 389, 1956.
Sekera, Z.	Gerlands Beitr. Geophys. 44, 157, 1935.
Sekera, Z.	Handbuch der Physik 48, 288-328, 1957.
Sekera, Z., et al	Rev. Sci. Instr. 34, 764, 1963.
Serkowski, K.	Advances in Astronomy and Astrophysics 1, 289, 1962.
Vasilev, G. and A.I. Shapov	Planetary Space Sci. 11, 93, 1963.